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Observations from aircraft of temperatures and humidities near stratocumulus cloud

by

D. G. James

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AIR MINISTRY

METEOROLOGICAL RESEARCH COMMITTEE

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1. Introduction

Previous work on the dissipation of stratocumulus cloud (James, 1955) suggested that certain features of the environment of the cloud sheet are significant in determining the subsequent behaviour of the cloud. In particular, a significant difference was thought to exist in the hydrolapses above and below cloud, the temperature lapse rate above cloud, and the cloud thickness between cases when the cloud sheet persisted and cases when it dissipated within a given time. As lack of better agreement may have been due to inaccuracies in surface observations of cloud base, and in radio sonde measurements of temperatures and dewpoints, it was recommended that a series of flights should be made by aircraft of the Meteorological Research Flight in order to make accurate measurements of some of the features associated with an extensive sheet of non-frontal stratocumulus cloud.

Flights subsequently carried out by the Meteorological Research Flight were such that, following an ascent from ground to about 10,000 ft, the aircraft made level runs of 3-5 min at 250 ft intervals from 1,000 ft below cloud base to cloud top, then at 100 ft intervals up to 500 ft above cloud top, thereafter at 250 ft intervals to 2,000 ft above cloud top, and finally two level runs of 8 min at 200 ft above cloud top and 200 ft below cloud base. Height, airspeed, temperature and frost point were observed every 250 ft on the ascent, and every 30 sec on the level runs along which the observations were supplemented by accelerometer records. In cloud, an attempt was made to obtain measurements of the liquid water content.

Selection of the occasions for the flights was made in the Forecasting Research Division, Dunstable, and the analysis of the flight data was also carried out there. Some modifications of the flight plan were made from time to time, but these did not affect the basic scheme.

To conform with operational requirements all flights were performed in the Farnborough area so that the aircraft could be followed by radar whilst flying in cloud.

2. Flights by M.R.F. aircraft

Eight flights were made during November, 1955 by aircraft of the M.R.F. in connection with the stratocumulus investigation. On four of these flights only an ascent and descent through the cloud was made, but on the remaining four flights a full set of data was obtained. Figs. 1 (a - h) show the vertical distribution of temperature and dewpoint as obtained from the aircraft observations, together with details of the cloud base and top.

/Although

Although temperatures and frost points cannot be measured accurately in cloud, there were occasions when the stratocumulus was quite thin and tenuous, and then readings were taken of temperatures and sometimes frost points also. These values have been included in Figs. 1 (a - h) where they occur.

The second half of November, 1955 was particularly favourable for the presence of extensive sheets of stratocumulus cloud. An anticyclone at first centred over Scotland moved slowly westwards, and then slowly returned, finally turning southeast and moving into France. In general during this period, southeast England was in an anticyclonic weak northeasterly flow which was accompanied by extensive stratocumulus cloud; sometimes the cloud dissipated. Table 1 gives the dates of the flights together with cloud bases and tops and probable times of dissipation.

On level runs near the cloud, an accelerometer was used. Some of the traces from one of the flights are given in Fig. 5. These are traces obtained on the flight of 14th November, 1955, but they are quite characteristic of all such records made near stratocumulus cloud.

3. Analysis of observations

3.1 Temperature

Temperature measurements were made by a flat plate thermometer, the lag of which is about 8 sec. A level run of 3-5 min allows ample time for the thermometer to settle down and the readings obtained will give a good indication of actual fluctuations of temperature along the aircraft track at a given height. In Figs. 1 (a - h) one of the vertical profiles is obtained by plotting the means of corrected temperatures recorded on level runs. It can be seen that the inversions of temperature immediately above cloud top as shown by these means are considerably greater than might be expected from an appropriate radio-sonde ascent, Figs. 2 (a - d). Furthermore, the measured temperature gradients in the inversion increase as the height interval between observations is decreased.

If there is turbulent mixing at cloud top then large temperature fluctuations should be apparent at cloud top. Figs. 3 (a - d) present the standard deviations of temperature measured on level runs at given heights. It is clear that in all four cases there is a large increase in the standard deviation of temperature at cloud top. A return to normal values of standard deviation is indicated at 200 ft above cloud top and at greater heights. It must be pointed out, however, that the standard deviations recorded are not true deviations of horizontal temperature. The variations in height of the aircraft on a horizontal run probably account for some of the observed fluctuations, though the altimeter records are not sufficiently accurate to obtain a good correlation between temperature and height variations. Little significance can be attached to absolute values of temperature measured in cloud due to the liquid water deposited on the thermometer, but it is thought that the temperature fluctuations are of the right order of magnitude, and they have been included in Figs. 3 (a - d).

Table 2 shows the lapse rates of temperature upwards from cloud top over various distances.

Figs. 1 (a - h) show that:-

(1) when level runs are made at 100 ft intervals above cloud top the estimated temperature gradients in the inversion directly above cloud are significantly greater than when measurements are taken every 250 ft on an ascent. Thus to obtain accurate measurements of $\Delta T/\Delta Z$ above cloud, temperatures must be obtained at intervals of 100 ft or less.

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(2) The gradient of temperature with height within 300 ft of cloud top is of the order of 3°C per 100 ft.

(3) In some cases, the inversion extends as far as 1,000 ft above cloud top, though in general there is a reversal of sign of $\Delta T/\Delta z$ within 5-600 ft.

(4) On the occasions when the cloud had already dispersed or was well broken, the inversions were not as intense as on the other occasions.

(5) Below cloud the measured temperatures indicate the presence of a dry adiabatic lapse rate.

3.2. Frost point

Frost points were measured by a Dobson-Brewer manual hygrometer. In the range in which observations of frost points and dewpoints were taken, i.e., -20°C to +10°C, this instrument is accurate to within 0.5°C. The instrument suffers from the disadvantage that frost points are obtained manually, and hence, in general, the readings obtained are not synchronous with the temperature observations. Further, in a region where the humidity is variable, the frost point measurements are frequently missed by over-shooting from one reading to the next.

Figs. 1 (a - h) show the profiles of dewpoints with pressure for the eight flights made. In all cases it is clear that there is a sharp decrease of humidity just above cloud top. On some occasions the cloud was so thin and tenuous that frost points were measured in the cloud layer, and the corresponding dewpoints have been shown in the figures. Nevertheless, complete saturation was not measured.

Figs. 4 (a - d) present the standard deviation of frost points measured on level runs near cloud. The standard deviations shown may be expected to be less than those which would have been obtained had a fully automatic hygrometer been used: with a fluctuating frost point there will be a tendency to record fewer observations with the manual hygrometer; also there will be considerable bias towards recording successive values of the frost point which are approximately of the same value. Thus the tendency for an increase in the standard deviation at or just above cloud top is probably real.

It is interesting to note that both the standard deviations of temperature and frost point recorded on 14th November, 1955, Figs. 3 (a) and 4 (a), are considerably greater over an 8 min run above cloud than for a 3 min run at the same height. For the 16th November, 1955 and 22nd November, 1955, Figs. 3 (b) and 4 (b) and Figs. 3 (c) and 4 (c), there is no significant difference between standard deviations over 8 min and those over 3 or 5 min. Examination of the individual values of temperature and frost point recorded on the 8 min run at 5,800 ft on 14th November, 1955 shows that the temperature increased throughout the run, whilst the frost points decreased, the wet bulb potential temperature remaining constant, and equal to that above cloud. However, during this 8 min run, the aircraft increased height by about 80 ft, which, using the slope of the inversion directly above cloud, would lead to an increase in temperature of about $1\frac{1}{2}$ to $2\frac{1}{2}$°C. This would account for nearly all of the discrepancy between the standard deviations recorded on the 3 min and 8 min runs at the same height. It should be emphasised that the so-called level 3-5 min runs frequently admitted of variations in height of up to ± 20 or 30 ft.

In general the values of $\Delta x/\Delta z$ obtained from Figs. 1 (a - h) are less than ± 0.3 gm/Kg per 100 ft, but above cloud there is a sudden increase when values of up to -1.5 gm/Kg per 100 ft are measured.

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The case of the 15th November, 1955, when there was no cloud, and that of the 21st November, 1955, when the cloud was well broken, are worthy of note. Both show that a significant change in the lapse rate of humidity mixing ratio is still present; on the other hand Figs. 1 (b) and 1 (f) do not indicate the presence of such a sharp temperature inversion on those dates as on the occasions of continuous cloud sheets.

3.3. Accelerometer records

A photographically recording accelerometer was used on most of the flights on which level runs were made. Figs. 5 (a - g) show sections of the traces obtained near cloud during the flight of 14th November, 1955. The traces are typical of the bumpiness experienced by the aircraft on all other flights near cloud base and top.

On all occasions when accelerometer records were obtained the traces well above cloud top were very different from those just above and below cloud top. The former, as can be seen from Fig. 5, exhibit considerably fewer bumps than do the latter, though the occasional bumps, when they do occur, are of comparable magnitudes with those experienced below cloud top. However, the most striking difference between the two sets of traces is the almost complete absence of high frequency (1 - 3 c/s) disturbances i.e., disturbance with spatial dimensions of 80 - 250 ft in the region well above cloud top. The natural frequency of the loaded spring constituting the accelerometer is 3 c/s, but the change in the character of the trace must correspond to a decrease in the small scale turbulence in the atmosphere. High frequency components are clearly evident in Figs. 5 (a - d) but almost entirely absent in Figs. 5 (e - g). The line of demarcation between the two types of traces is well marked. On all occasions the sharp division occurred between 200 and 300 ft above cloud top; the traces above this height are very smooth, increasingly so with height, whilst below this level the traces are extremely disturbed. Accurate assessment of vertical velocities from the accelerometer traces (see Jones, 1953) was found to be impossible since a recording altimeter was not used, and therefore the zero error could not be applied accurately to the integrated traces. There was also considerable doubt in some cases as to the speed of the film in the accelerometer.

4. Discussion

4.1. General considerations

Although eight flights were carried out by the M.R.F. aircraft, full sets of data were obtained on only four of them. Consequently the following discussion relates only to these four cases though there is no evidence that the profiles obtained from the remaining four flights were materially different.

For the flights considered the stratocumulus sheet had been in existence for some 10 hours or more, and persisted for some hours afterwards. It is unlikely, therefore, that at the times of observation the observed temperature and humidity structures were changing rapidly.

The effect on the cloud of the following processes will be considered:-

(a) Radiation

(b) Turbulent diffusion of heat and water vapour at cloud base and top

(c) Subsidence.

It is not proposed to consider advection because the stratocumulus sheets extended well upstream and downstream from the area of flight and successive radio-sonde soundings showed no change in air mass.

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The remaining processes are considered below with particular reference to the data of 14th November, 1955, but corresponding results for the other three cases of complete data will be given later in the discussion.

4.2. Evidence from flight measurements

All flights in the region of a stratocumulus cloud sheet indicate the presence of a marked inversion extending for 10 mb or so above cloud top surmounted by at least a further 20 mb of very dry air with a stable lapse rate. The accelerometer records indicate significant turbulence in the lower part of the inversion layer directly above cloud.

The observed turbulence will transfer heat downwards into cloud top and water vapour upwards into the inversion layer and tend to change the observed character of the temperature inversion and hydrolapse. However, since these latter are fairly constant from flight to flight it is necessary to explain how the observed character of the inversion layer is maintained. Moreover, although the flights were of limited duration, there was little indication of systematic changes in the level of cloud top during them. We are therefore led to the conclusion that the air immediately above cloud top is continually being replaced by subsidence which operates against the turbulence to give an approximately steady state at and immediately above cloud top.

Before we evaluate the rate of subsidence necessary to maintain a steady state, we will first consider the heat and water vapour budgets of the cloud and air below and also those of the inversion layer. In the calculations we will make an initial choice of 3×10^3 cm^2/sec for the value of the coefficient of eddy diffusion, K, appropriate to the inversion layer, both in respect of heat and water vapour. This is the value given by Taylor (1915) for stable conditions at lower levels over the sea with winds of about 10 kt. The effect of a different value of K will be evident at any stage and indeed we shall see later that it is necessary to consider other values.

4.3. The heat budget of the cloud and air below

4.3.1. Radiation

Radiation measurements above a stratocumulus or stratus cloud sheet (Neiburger, 1949, Fritz, 1950, Murgatroyd, 1956) suggest that the albedo of such a sheet varies considerably with cloud thickness. Values between 0.3 and 0.8 are given for thicknesses from 'very thin' to 4,500 ft. For a cloud about 500 ft thick an albedo of 0.5 is probably close enough for our purposes.

Measurements at Kew show that, during a clear day in November, about 180 cal/cm^2 are available at the surface from solar radiation, an average of 20 cal/cm^2/hr between sunrise and sunset. Other measurements (Berry, Bollay and Beers, 1945, Houghton, 1954) also suggest an average during November of about 20 cal/cm^2/hr at the surface at about latitude 50°N. In the calculations below it is more convenient for us to assume durations of 8 and 16 hours for day and night respectively in November; also some allowance has to be made for the fact that events at a height of about 5,000 ft are under consideration. It will therefore be assumed that during daylight hours in November an average of about 25 cal/cm^2/hr is available at 5,000 ft from solar radiation. Thus with an albedo of 0.5 about 13 cal/cm^2/hr pass into cloud top.

The loss of heat by long-wave radiation at cloud top may be obtained by use of the Elsasser radiation chart. For 14th November, 1955 this loss was about 10 cal/cm^2/hr.

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Thus during the day there is a flux of heat of about 3 cal/cm^2/hr downwards through cloud top, whilst at night there is an outward flux of 10 cal/cm^2/hr.

The long-wave radiative loss occurs in the top 50 ft or so of the cloud and consequently this thin layer will at all times be tending to cool rapidly. Convective turbulence must therefore occur, causing rapid mixing of the air within the cloud; also mixing with the dry air below in which the observed lapse rate is dry adiabatic over a considerable depth. Thus cooling initiated at cloud top is quickly spread over a considerable depth below.

4.3.2. Conduction and evaporation

Measurements made at Kew suggest that, during November, about 1 cal/cm^2/hr is conducted into the earth during the day, the heat being restored to the surface at the same rate during the night.

The evaporation of water at the surface accounts for some heat also. Data available in the British Climatology Branch of the Meteorological Office show that evaporation from tanks of water at Kew was at the rate of about 7×10^{-2} gm/cm^2/24 hr on the dates of the flights. It is known that the average rate of evaporation during the day is some 3 or 4 times that at night. We will therefore assume that the average rates of evaporation during the day and night on the dates of the flights were 6.0×10^{-3} gm/cm^2/hr and 1.5×10^{-3} gm/cm^2/hr respectively. The quantities of heat required for these rates of evaporation are approximately 4 cal/cm^2/hr and 1 cal/cm^2/hr.

4.3.3. Turbulence

In the case of 14th November, 1955, assuming a saturated adiabatic lapse rate in the cloud and also a linear variation of temperature with pressure from cloud top at 851 mb to the top of the inversion at 838 mb, then the average $\Delta\theta/\Delta p$ (θ is potential temperature) through the stable layer is 0.44°C/mb. The flow of heat downwards is thus

$$F = \rho C_p K \frac{T}{\theta} \frac{\partial \theta}{\partial z} \simeq 1 \text{ cal/cm}^2\text{/hr}$$

taking $K = 3 \times 10^3$ cm^2/sec.

4.3.4. Summary of heat budget of cloud and air below

The above figures show that during the day the net loss of heat by the cloud and air below would be 1 cal/cm^2/hr. Assuming that this loss is uniformly distributed from cloud top to ground - all flights show a dry adiabatic lapse rate in a layer of some depth below cloud base - the cloud and air below cools by about 0.2°C during daylight hours.

At night there would be a net loss of 9 cal/cm^2/hr giving a cooling of the cloud and air below of 3.3°C during the night. This is about twice as great as is actually observed from radiosonde ascents at 12 hr intervals through the same air mass, and must therefore be considered further.

The main factor responsible for the rate of cooling thus calculated is the radiative loss from cloud top evaluated as 10 cal/cm^2/hr using the Elsasser diagram. However, measurements from aircraft of the flux of long-wave radiation near

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stratocumulus cloud by Houghton and Brewer (1955) (about 9 cal/cm^2/hr at night) confirm the value we have taken. We must therefore turn to some other factor to operate against this excessive rate of cooling. Possibly the value of K we have assumed (3×10^3cm^2/sec) is too low, especially at night. A value of K of 10^4cm^2/sec would, through more rapid transfer of heat downwards in the inversion layer (4 cal/cm^2/hr), restrict the cooling of the cloud and air below to 2.2°C during the night, and this is much nearer what is observed. There is thus some indication that we may need to consider the effect of values of K greater than 3×10^3cm^2/sec in the inversion layer.

4.4. The water vapour budget of the cloud and air below

4.4.1. Evaporation

From 4.3.2. the water vapour available through evaporation at the surface is about 6.0×10^{-3}gm/cm^2/hr by day and 1.5×10^{-3}gm/cm^2/hr by night. Since all flights show that the humidity mixing ratio is constant in a considerable depth below cloud base, it is likely that the turbulence, as shown by the accelerometer traces, is sufficient to distribute the evaporated water through the cloud and air below.

4.4.2. Turbulence

The cloud loses water vapour by turbulent diffusion upwards at cloud top. The measurements of water content in the cloud are not reliable but it is reasonable to assume that the humidity mixing ratio in the cloud (including liquid water) is determined by observed temperature immediately below cloud base (dry adiabatic lapse) and the observed level of cloud base, extended upward by a saturated adiabatic lapse rate in cloud. Then for the data of 14th November, 1955, the average hydrolapse $\Delta x/\Delta p$ through the inversion layer immediately above cloud is 0.20×10^{-3}gm/gm/mb so that the flux of water vapour upwards is

$$F = \rho K \frac{\partial x}{\partial z} \simeq 2.2 \times 10^{-3}\text{gm/cm}^2\text{/hr},$$

using $K = 3 \times 10^3$ cm^2/sec.

4.4.3. Summary of the water vapour budget of the cloud and air below

During the day there would be a net gain of water vapour of 3.8×10^{-3}gm/cm^2/hr by the cloud and air below; by night a loss of 0.7×10^{-3}gm/cm^2/hr. Thus the changes in humidity mixing ratio of the air below cloud top would be about +0.2 gm/Kg during daylight hours and -0.06 gm/Kg by night, K being 3×10^3cm^2/sec. For $K = 10^4$ the changes would be -0.05 gm/Kg by day and -0.5 gm/Kg by night.

4.5. The balance of the inversion layer

The accelerometer records indicate considerable turbulence in and below the layer from cloud top to about 10 mb above but none whatever higher up in the dry air. It must therefore be assumed that the heat gained by the cloud and air below through turbulent diffusion, is taken entirely from this layer; also that the water vapour lost by the cloud and air below is accumulated in this layer. As we have seen in 4.2. above this would lead to observable changes in temperature and humidity in this layer and changes in the character of the temperature and dewpoint profiles in and immediately around the inversion. As no systematic variation in the level of cloud top was observed on any flight we proceed to calculate

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the rate at which the air in the inversion layer needs to be replaced by subsidence in order to counteract the effects of turbulent transfer and to maintain cloud top at the same level.

If air is subsiding then the amount of heat added to a layer is proportional to the rate of subsidence and to the difference in potential temperature at the limits of the layer. In the case of 14th November, 1955, the assumptions in 4.3.3. give a difference of 6°C in the potential temperature at cloud top at 851 mb and the top of the inversion at 838 mb. Thus a subsidence rate of rather less than 1 mb per hour would be sufficient to balance the heat loss to the cloud by turbulence (1 cal/cm^2/hr with $K = 3 \times 10^3$).

Similarly if the transport of water vapour downwards by subsidence is to equal that upwards by turbulent diffusion; then, with the assumptions given in 4.4.2., taking an average value of 2.6 gm/Kg for the humidity mixing ratio in the inversion layer, a rate of subsidence of rather less than 1 mb/hr is also sufficient to balance the upward transfer of water vapour by turbulence in the inversion layer.

The rate of subsidence required for this balance is directly proportional to the value of K assumed to be operative in the inversion layer. With $K = 10^4$ subsidence of rather less than 3 mb/hr would be required.

It will be appreciated that when subsidence operates there is divergence out of any column of air extending from cloud top to the ground. However, the heat and water vapour budgets of the cloud and air below remain as above (we assume constant potential temperature and humidity mixing ratio below cloud).

4.6. Extension to the four cases of complete data

Table 3 presents the results of calculations on all four occasions of complete data, carried out in the same manner as in 4.3. to 4.5. above. The table also includes estimates of the behaviour of the cloud if the assumed conditions were operating, and also the observed behaviour of the cloud. We will summarise here the assumptions made in obtaining the figures.

4.6.1. Complete saturation was not observed in cloud on any flight. The observations of humidity in the cloud were therefore regarded as unreliable and it was assumed that the (corrected) dry bulb temperatures below cloud (approximately on a dry adiabat for 50 mb at least) were correct. The humidity mixing ratio below cloud was assumed to be that given by these dry bulb temperatures and the observed cloud base. Similarly the temperature and frost point immediately above cloud top were assumed to be those determined by a wet adiabatic lapse rate in cloud.

4.6.2. The change in temperature and humidity mixing ratio of the cloud and air below were calculated on the assumption of complete mixing down to M.S.L. by both day and night. Whilst this is not necessarily true it gives a basis for comparison. As the relevant figures are inversely proportional to the layer mixed, adjustment for this assumption may readily be made.

4.6.3. Estimates of the observed behaviour of the cloud refer to the area of cloud near which the aircraft observations were made; so that, in determining from the synoptic chart whether or not it dispersed, an estimate of the movement of this parcel of cloud had to be made.

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4.7. Deductions

4.7.1. The value of K in the inversion layer

On at least three of the occasions considered in detail the flights occurred in mid-afternoon and it may be assumed that the observed conditions applied at sunset. We are therefore interested at first in the figures against night in Table 3. If the expected and observed behaviour of the cloud are compared, it can be seen that the operative value of K in the inversion layer must be at least 10^4 cm^2/sec, if not rather greater, by night, if the expected behaviour is to approach the observed behaviour. With a K of $3 \times 10^3 cm^2$/sec unreasonable rates of subsidence would be required to disperse the cloud in the first two cases by 6 hours after sunset. On the other hand, if the observed profiles existed at sunrise there would be some reason to believe that the operative value of K by day is less than $10^4 cm^2$/sec because in all cases the cloud persisted by day.

General considerations support the possibility that the value of K in our problem is higher than might otherwise be expected in inversions of the magnitude we are considering; and that the value by night could well be higher than that by day. Excluding orographic effects, the turbulence in the cloud is maintained by the cooling of the top 50 ft or so of the cloud by reason of the outgoing long-wave radiation; as no fixed boundaries are involved the convective turbulence thus caused must have an effect in the (shallow) inversion layer above cloud; moreover the turbulence in the cloud may be expected to be greater by night than by day due to absorption of solar radiation by day.

4.7.2. Subsidence

The rate of subsidence, neglecting the small amount which may result from night cooling, is a function of the general synoptic regime only and not, ceteris paribus, of the time of day. Thus if the rate of subsidence is greater/less than the figures given in Table 3 cloud top will fall/rise. Rates of subsidence substantially greater than those given to maintain cloud top at the same level, K being $10^4 cm^2$/sec, are unlikely in general. As we have seen that K may well exceed $10^4 cm^2$/sec in the inversion above a stratocumulus sheet by night, it is probable that, in most cases, cloud top rises by night; although the cloud may still disperse through decrease of the humidity mixing ratio below the inversion.

5. Conclusions

5.1. The temperature inversion and lapse rate of water vapour content above a sheet of stratocumulus cloud are considerably greater than those shown by a radio-sonde ascent through the same air mass. Temperature increases of up to 3°C/100 ft and lapse rates of humidity mixing ratio of up to 1.5 gm/Kg/100 ft have been measured. For all cases of continuous cloud sheets the change from the saturated cloudy air to the warmer drier air above occurred almost entirely within the first 300 ft above cloud top.

5.2. The standard deviations of the temperature fluctuations on level runs near the cloud may be of an order of magnitude greater in the first 300 ft above cloud top than at any other level. The standard deviations of frost points measured on these runs exhibit similar features, but the increase directly above cloud is less well marked. In general, the standard deviation of temperature is of the same order as that of frost point.

5.3. The accelerometer records for level runs near cloud show a marked change at 200-300 ft above cloud top. Few bumps were experienced above

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this height, and there was a complete lack of high frequency disturbances (1-3 cycles/sec) i.e., disturbances of spatial dimensions of 80-250 ft. It is suggested that eddies of these dimensions play a major part in the transport of heat and water vapour by turbulence.

5.4. Consideration of the observed temperature and humidity profiles together with the effects of radiation, turbulent diffusion of heat and water vapour, and subsidence lead to the conclusion that the approximately steady state in a persistent layer of stratocumulus is maintained by turbulence operating against subsidence.

5.5. It is probable that the operative value of K, the coefficient of eddy diffusion, in the inversion layer immediately above cloud is close to $10^4 cm^2/sec$; and that K is greater by night than by day.

5.6. With K = $10^4 cm^2/sec$, subsidence of 3 mb/hr would keep cloud top at the same level in the cases considered. Subsidence rates greater/less than 3 mb/hr would result in cloud top falling/rising.

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TABLE I

Date	Duration of flight	Cloud		Probable time of dissipation
		Base (ft.)	Top (ft.)	
14:11:55	1400 – 1630	5,250	5,500	2300/14
15:11:55	1500 – 1620	No cloud		—
16:11:55	1430 – 1700	3,150	4,000	2200/16
17:11:55	1520 – 1620	5,000	6,100	2200/17
18:11:55	1410 – 1525	4,200	5,000	Not before 0600/19
21:11:55	1430 – 1530	3,000	3,500 (well broken)	Possibly 1800/21
22:11:55	1340 – 1630	6,750	7,750	Not before 0600/23
28:11:55	1100 – 1330	4,250	4,750	Not before 0600/29

TABLE 2

Mean lapse rate from cloud top to specified heights above cloud top

$\frac{\Delta T}{\Delta Z}$ in °C / 100 ft.

		Height above cloud top (ft.)								
Date	Cloud cover	100	200	300	400	500	750	1000	1250	1500
14:11:55	8/8 sheet	3·06	1·81	1·37	0·95	0·85	0·49	0·32	0·25	0·18
15:11:55	Nil									
16:11:55	8/8 sheet	2·62	1·58	0·98	0·77	0·57	0·32	0·19	0·11	0·05
17:11:55	8/8 sheet	–	–	–	0·87	–	–	0·32	–	0·15
18:11:55	8/8 sheet	–	–	–	–	0·56	–	0·32	–	0·22
21:11:55	Well broken	–	–	-0·02	–	0·11	0·17	0·24	–	–
22:11:55	8/8 sheet	–	1·93	2·00	1·64	1·27	–	–	–	–
28:11:55	8/8 sheet	1·60	0·94	1·09	1·14	1·17	–	–	–	–

DATE AND TIME OF FLIGHT	M.S.L. PRESSURE (MB.)	CLOUD TOP (MB.)	CLOUD THICKNESS (MB.)	ASSUMED K (CM^2/SEC)	DAY 8 NIGHT 16 (HRS.)	CHANGE TEMP. CLOUD AND AIR BELOW °C PER DAY AND NIGHT	CHANGE HUM. MIXING RATIO CLOUD AND AIR BELOW (G M./KG. DAY/NIGHT)	SUBSIDENCE TO KEEP CLOUD TOP AT SAME LEVEL (MB./HR.)	EXPECTED BEHAVIOUR OF CLOUD +THICKNESS (MB. DAY/NIGHT)	OBSERVED BEHAVIOR OF CLOUD
14:11:55 1400-1630	1025	850	10	3×10^3	DAY	−0·2	+0·2	1	+15	CLOUD PATCHY WITH BREAKS BY DAY. OBSERVED AREA OF CLOUD PROBABLY DISPERSED 2200Z
					NIGHT	−3·3	−0·1		+40	
				10^4	DAY	+0·4	−0·1	3	−10	
					NIGHT	−2·2	−0·5		−5	
16:11:55 1430-1700	1040	900	25	3×10^3	DAY	0·0	+0·2	1	+10	DISPERSED 2200Z
					NIGHT	−3·7	−0·1		+40	
				10^4	DAY	+1·0	−0·1	3	−20	
					NIGHT	−1·7	−0·7		−20	
22:11:55 1340-1630	1035	780	22	3×10^3	DAY	0·0	+0·1	1	+5	PERSISTED AT LEAST OVERNIGHT
					NIGHT	−2·0	0·0		+25	
				10^4	DAY	+0·7	0·0	3	−5	
					NIGHT	−0·6	−0·2		0	
28:11:55 1100-1330	1020	860	12	3×10^3	DAY	−0·1	+0·2	1	+10	PERSISTED AT LEAST OVERNIGHT
					NIGHT	−3·4	−0·1		40	
				10^4	DAY	+0·6	−0·1	2 HEAT	−10	
					NIGHT	−2·0	−0·5	3W. VAPOUR	0	

Table 3 Estimates and observations on occasions of complete data

Fig. 1(a)
Aircraft
measurements
1400 - 1630
14:11:55

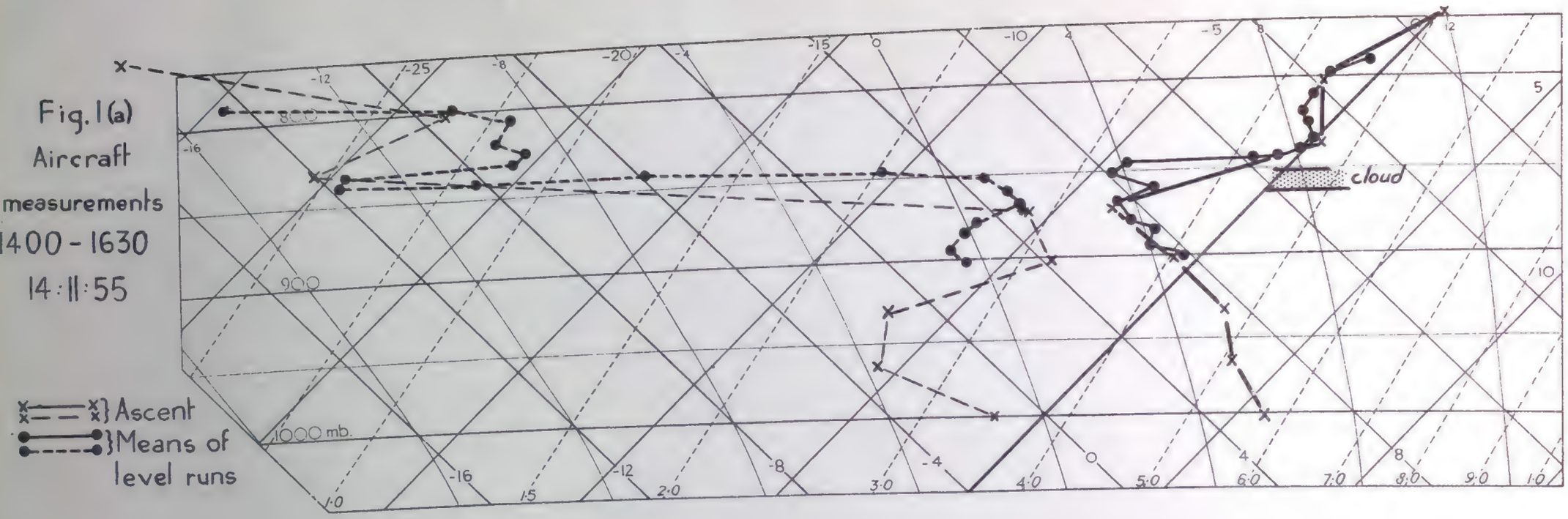
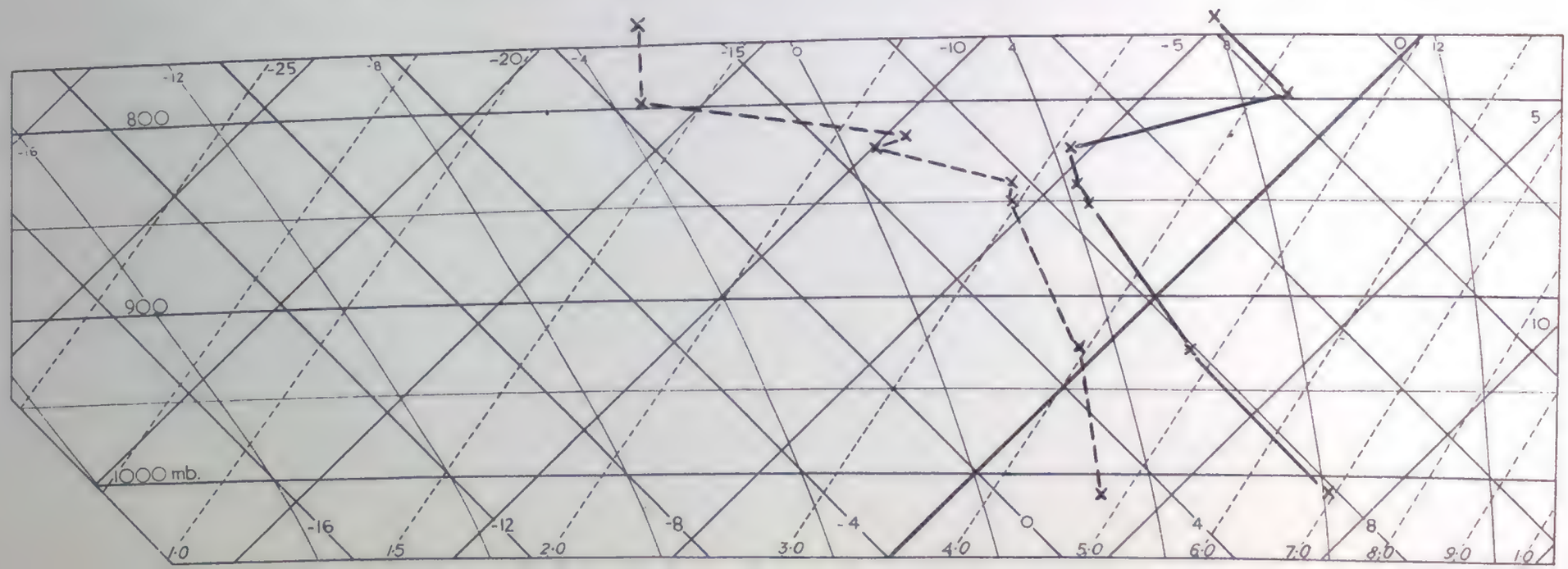


Fig. 2(a)
Crawley
1400



M.R.P. 1055

Fig 1(b)
Aircraft
ascent
1500-1620
15:11:55

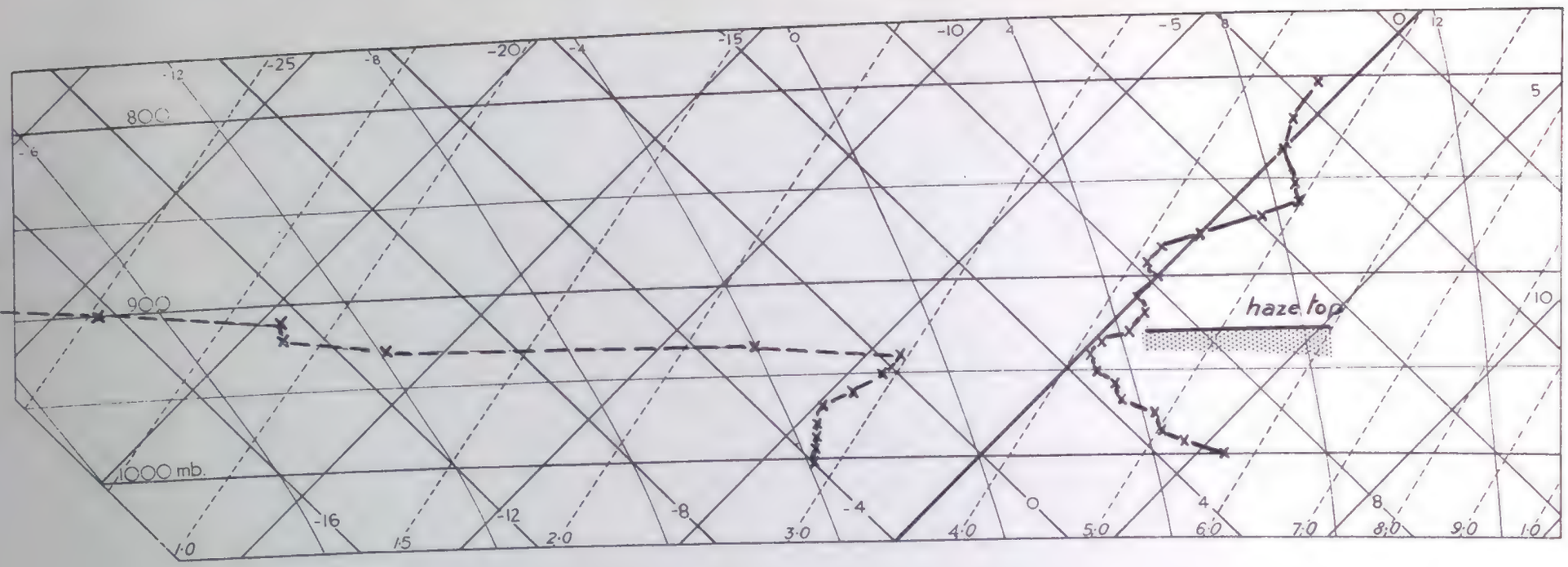
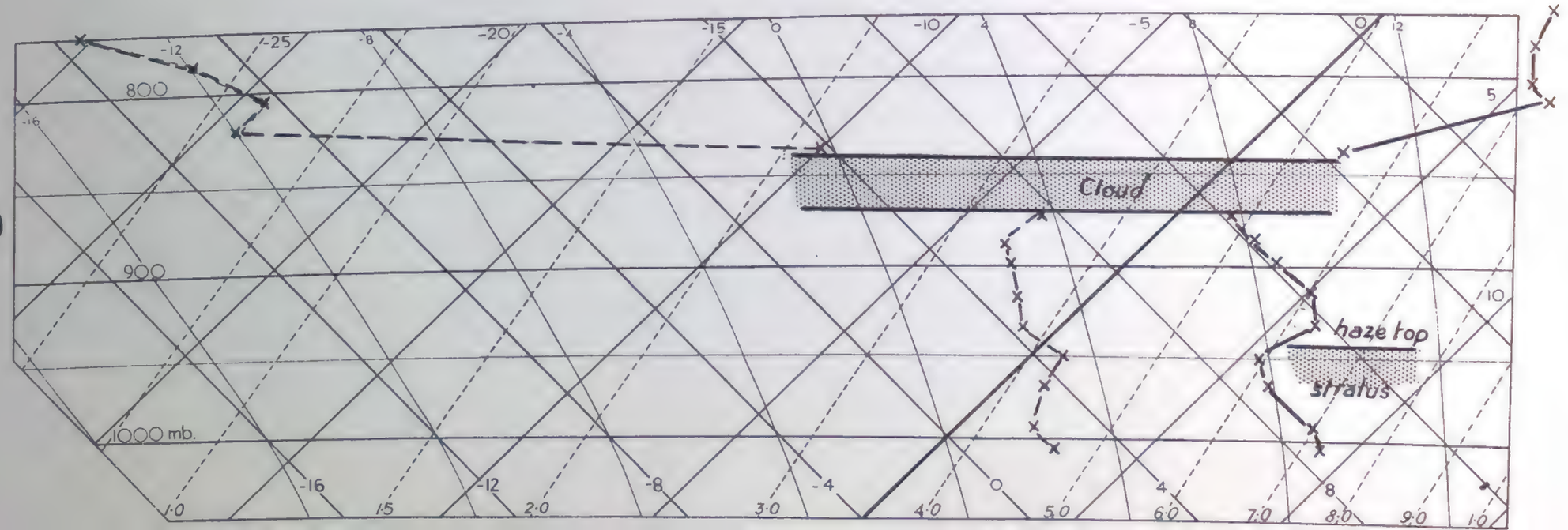


Fig. 1(d)
Aircraft
ascent
1520-1620
17:11:55



M.R.P. 1055

Fig 1(c)
Aircraft
measurements
1430-1700
16:11:55

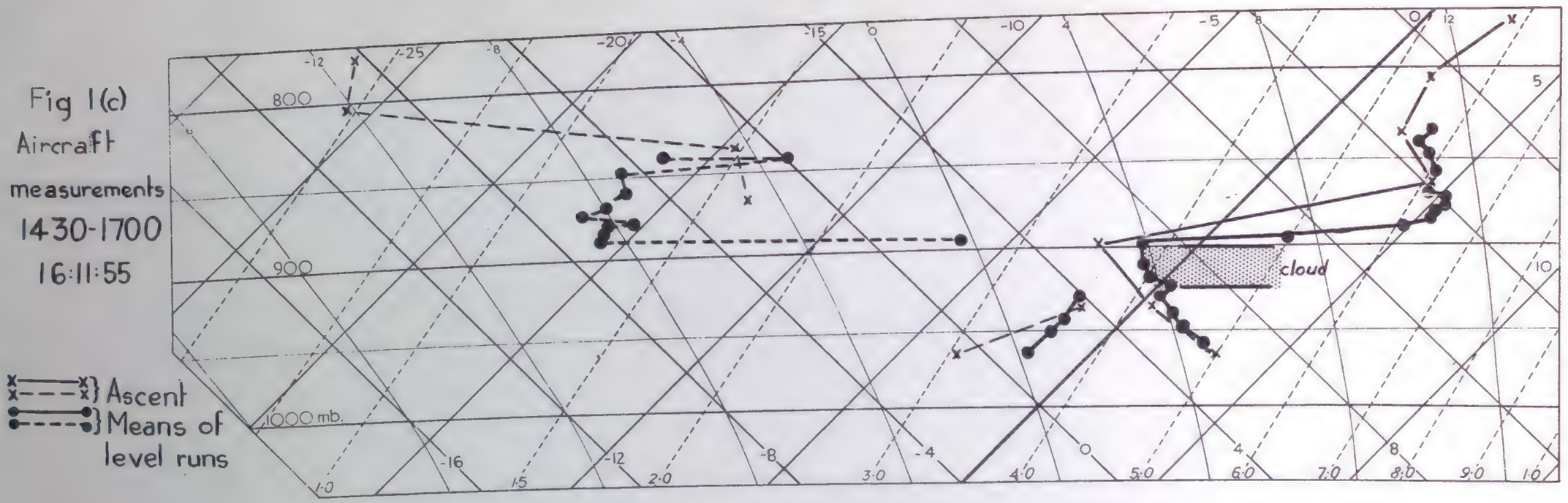
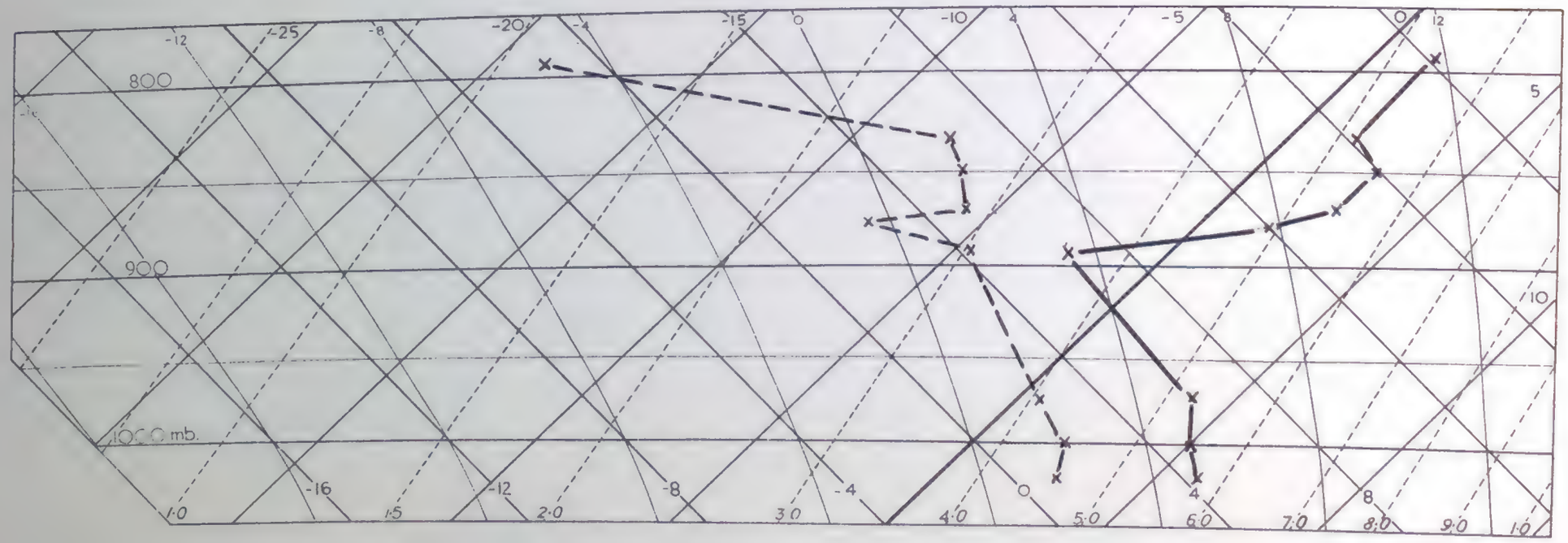


Fig. 2 (b)
Crawley
1400



M.R.P. 1055

Fig 1(e)
Aircraft
ascent
1410-1525
18:11:55

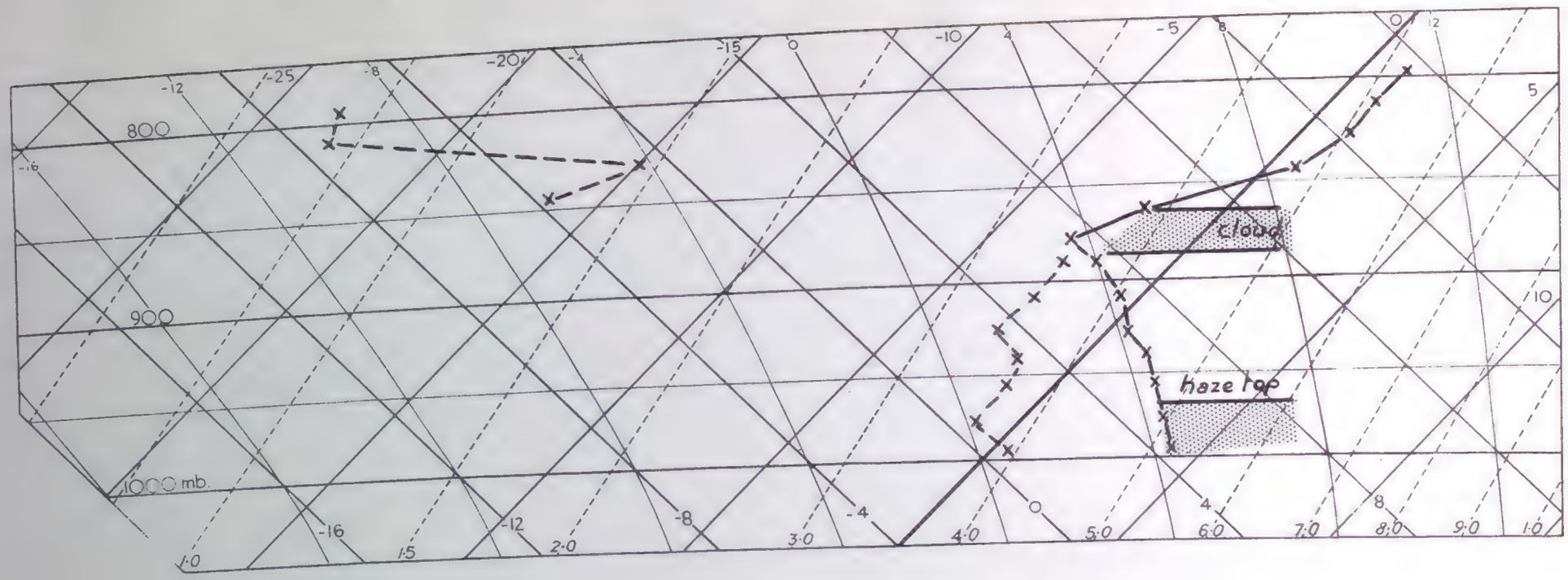
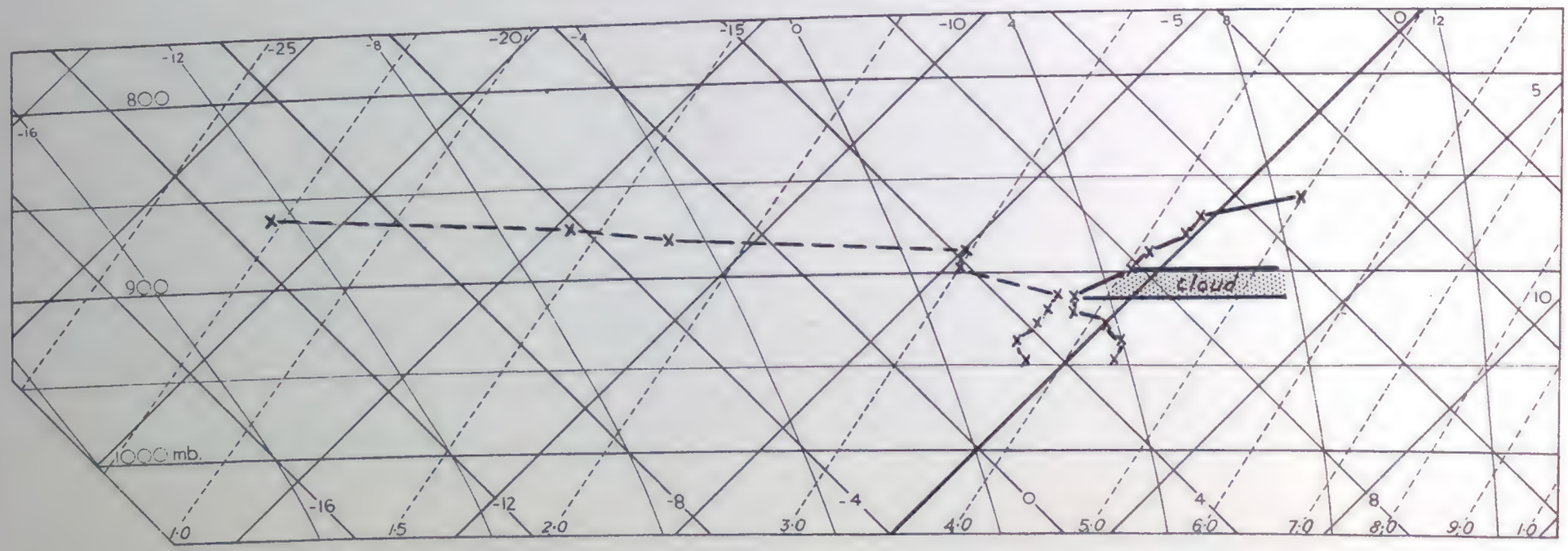


Fig. 1(f)
Aircraft
ascent
1430-1530
21:11:55



M.R.P. 1055

Fig. 1(g)
Aircraft
measurements
1340-1630
22:11:55

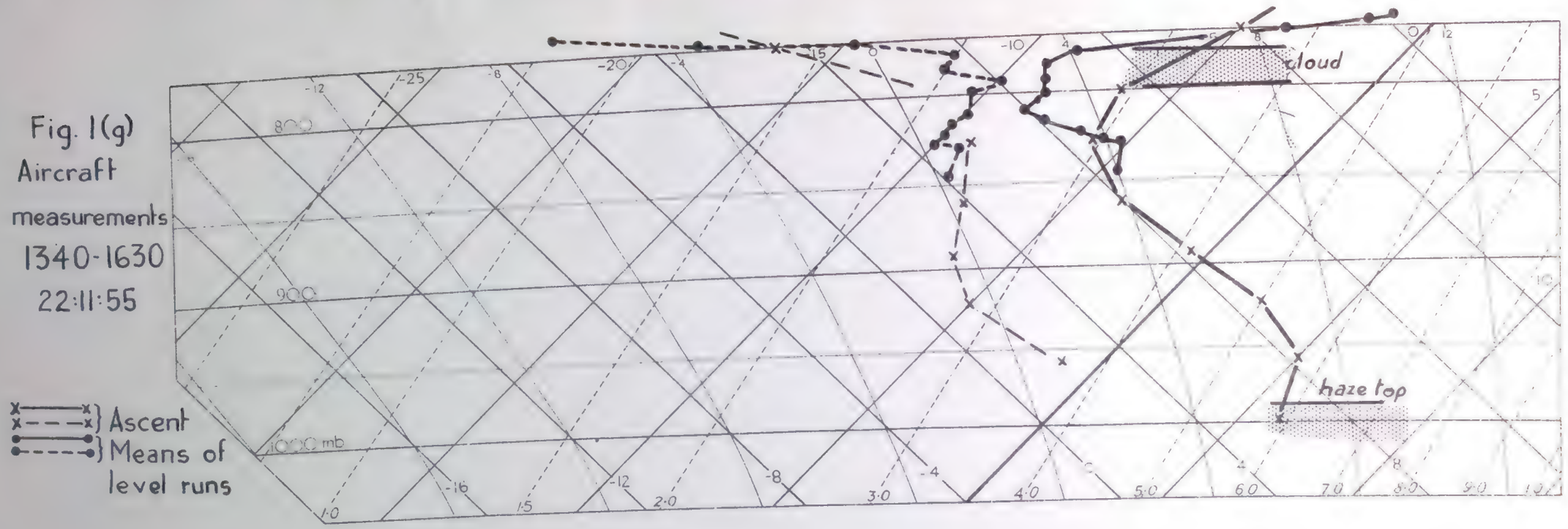
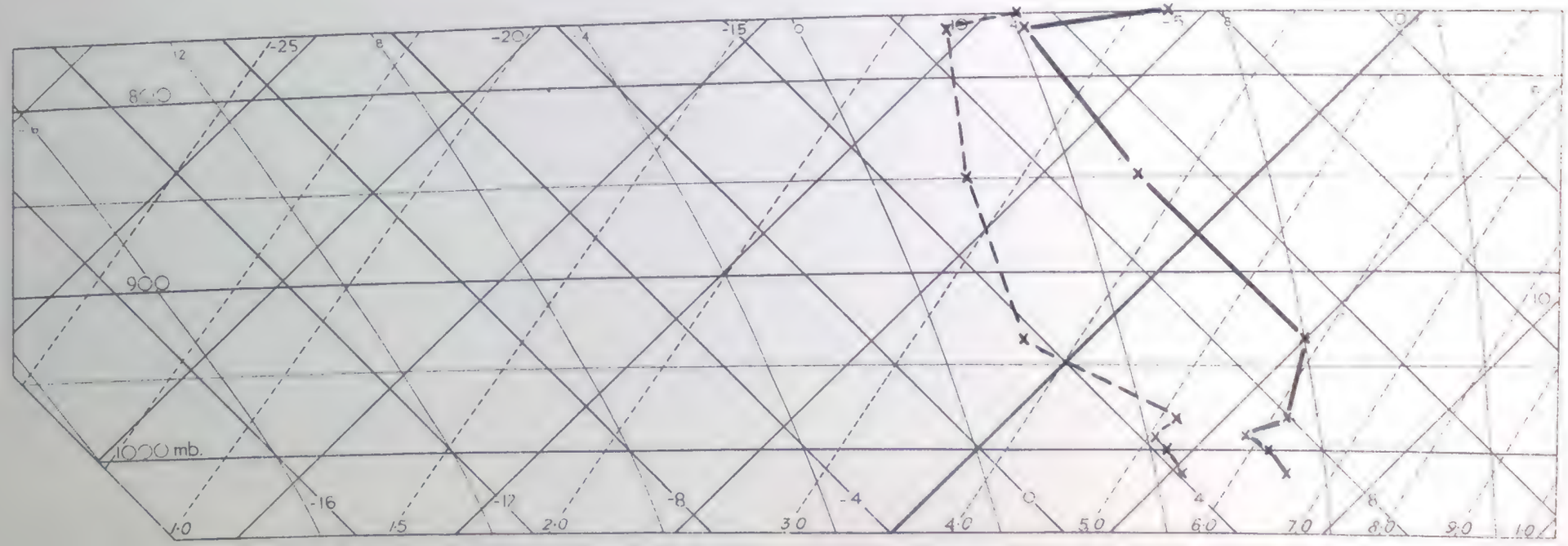


Fig. 2(c)
Crawley
1400



M.R.P. 1055

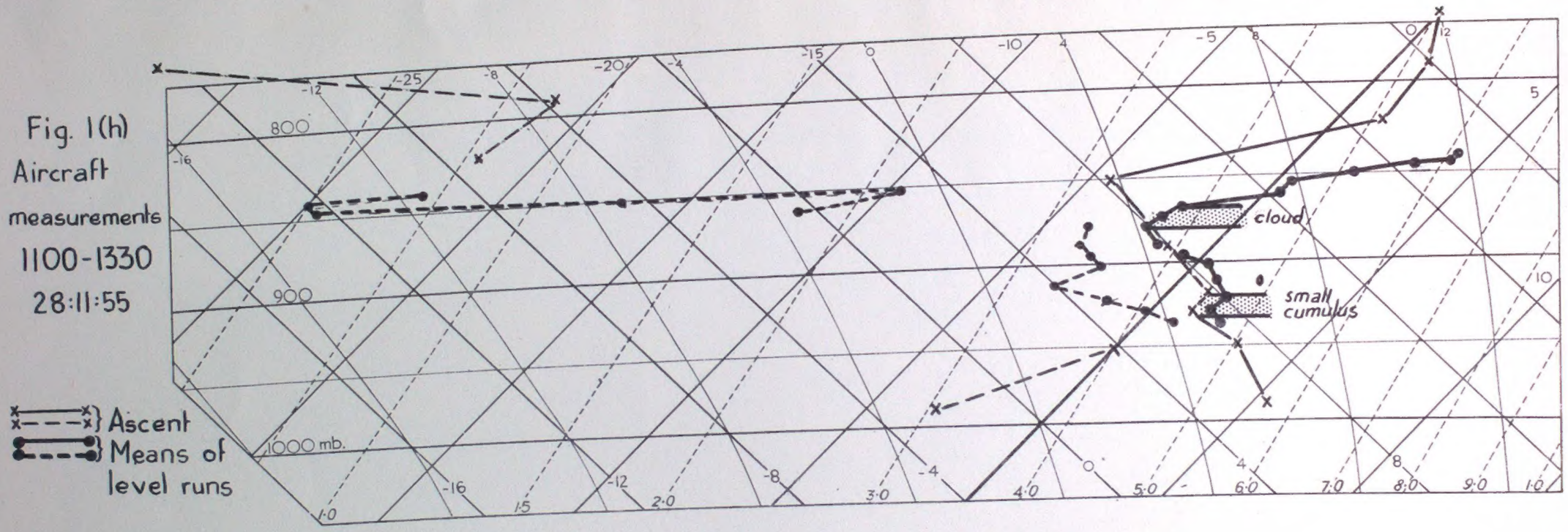


Fig. 1(h)
Aircraft measurements
1100-1330
28:11:55

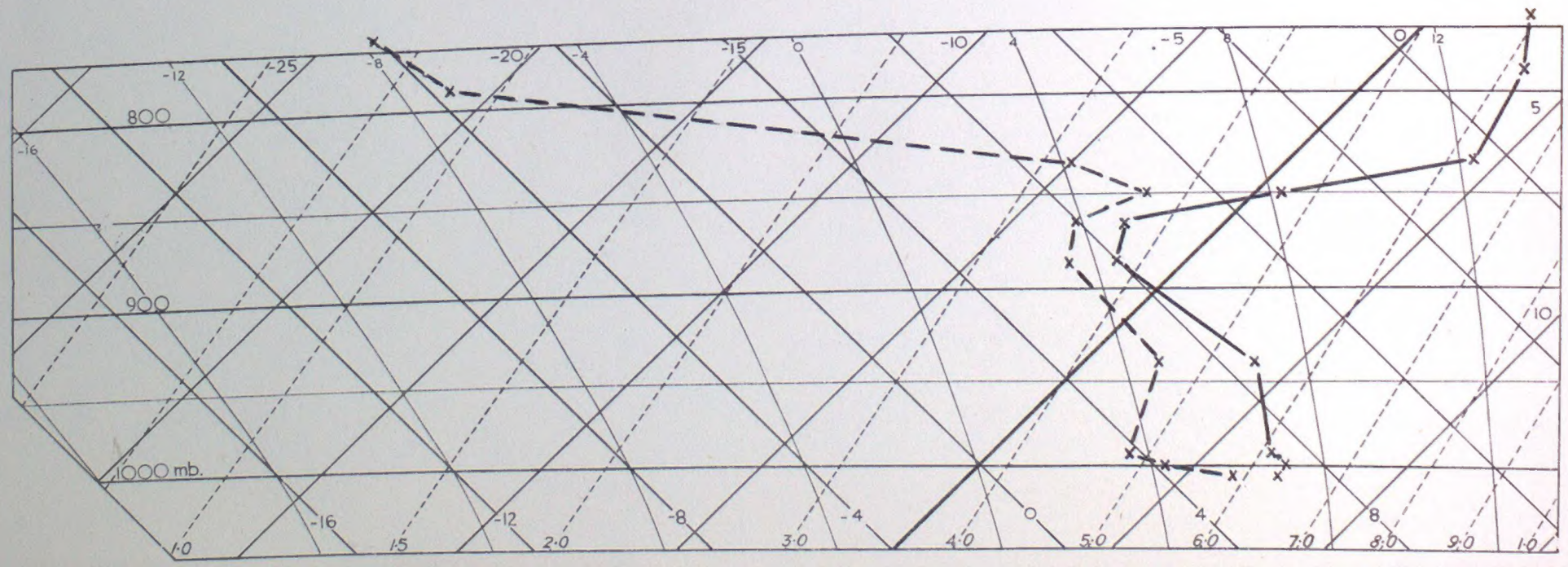
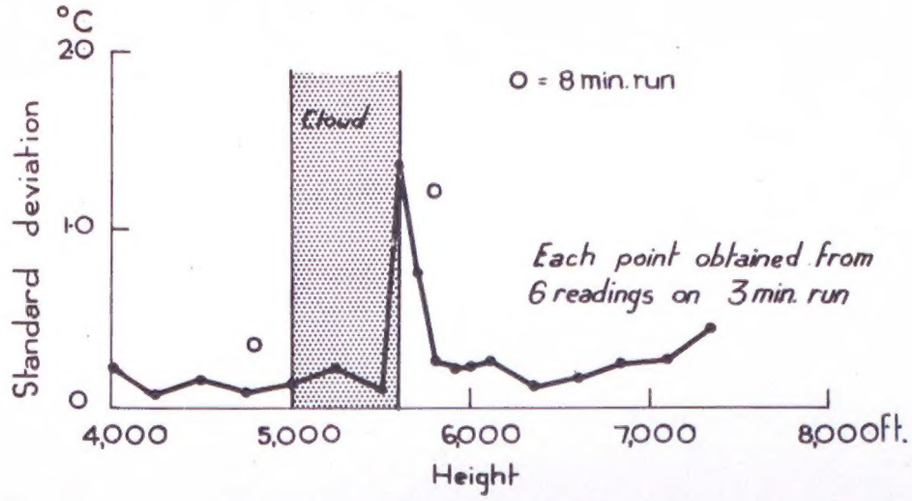


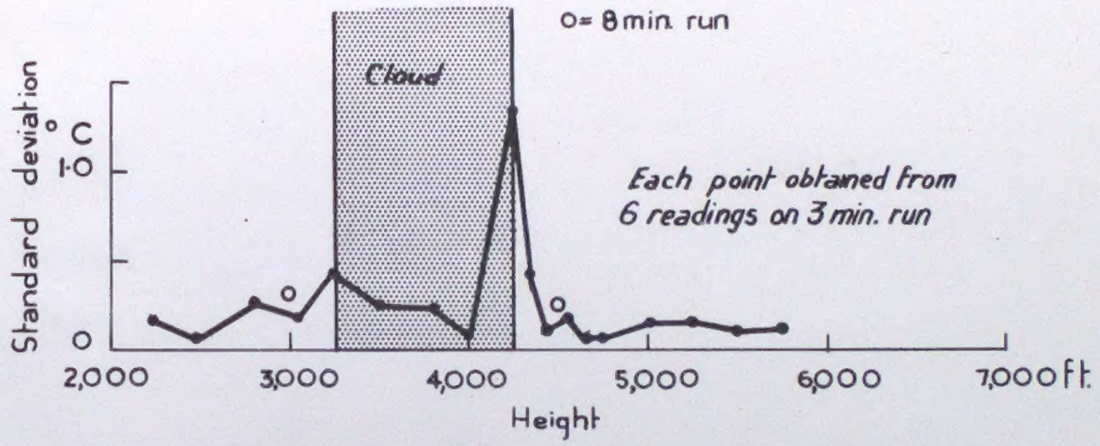
Fig. 2(d)
Crawley
1400

Fig. 3

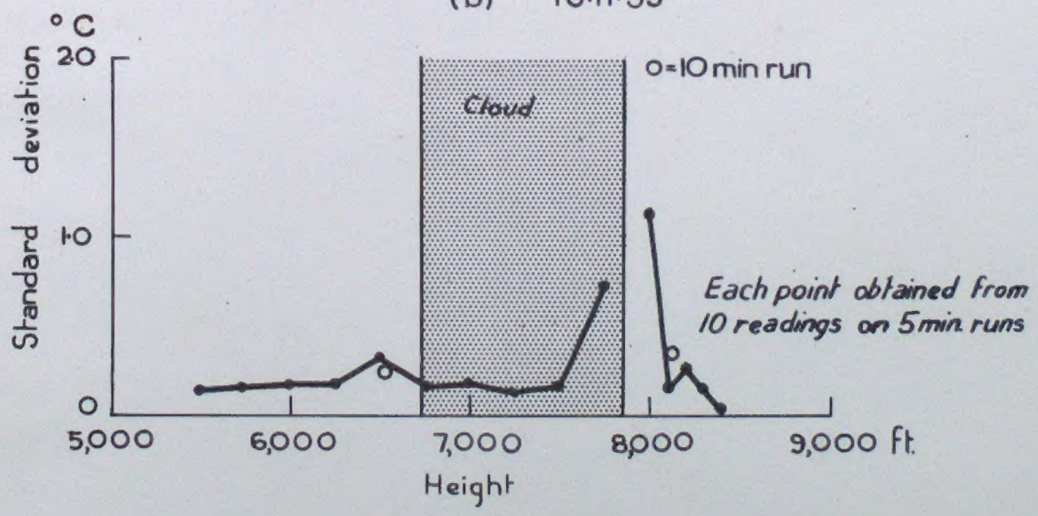
Standard deviations of temperature on level runs



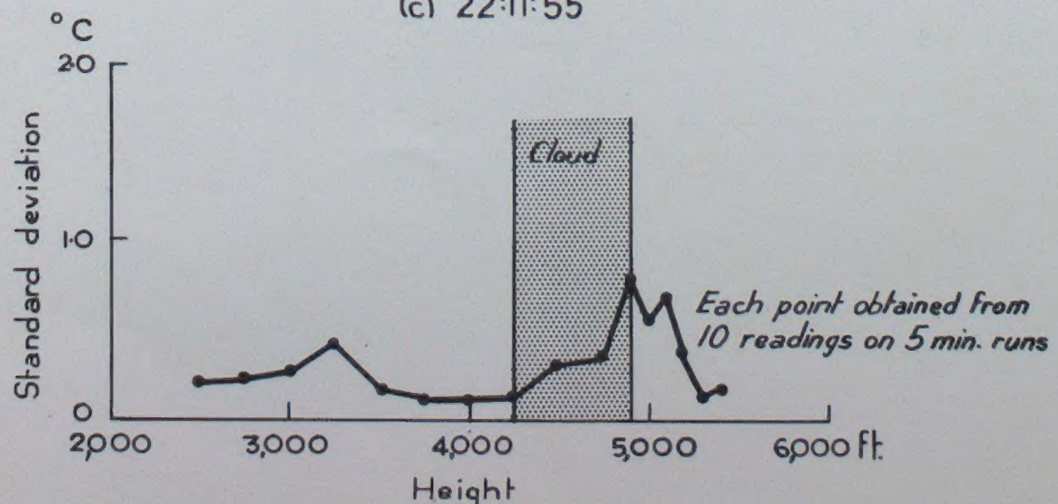
(a) 14:11:55



(b) 16:11:55



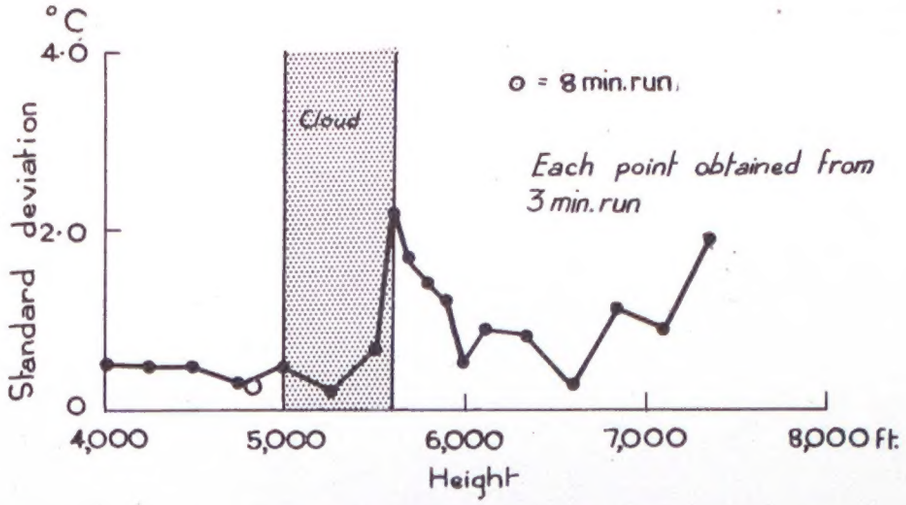
(c) 22:11:55



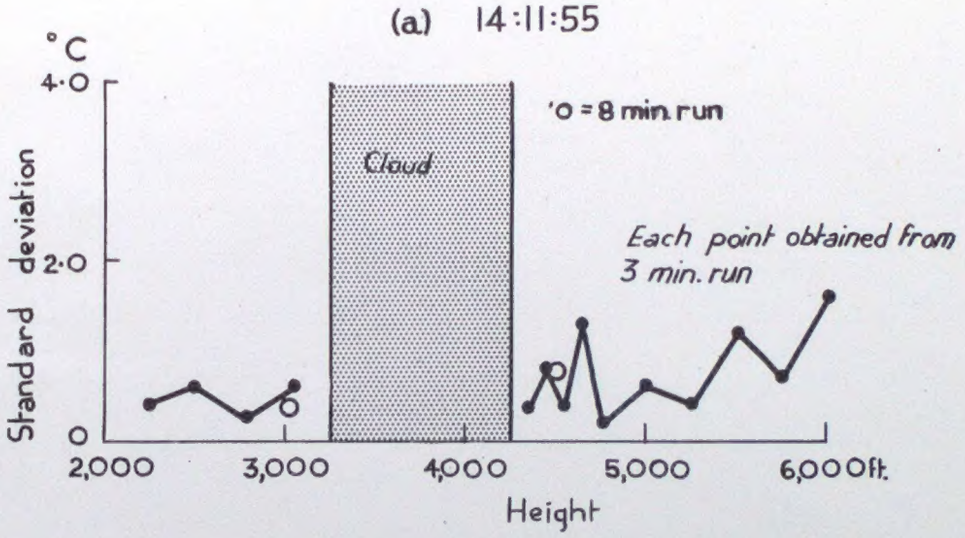
(d) 28:11:55

Fig. 4

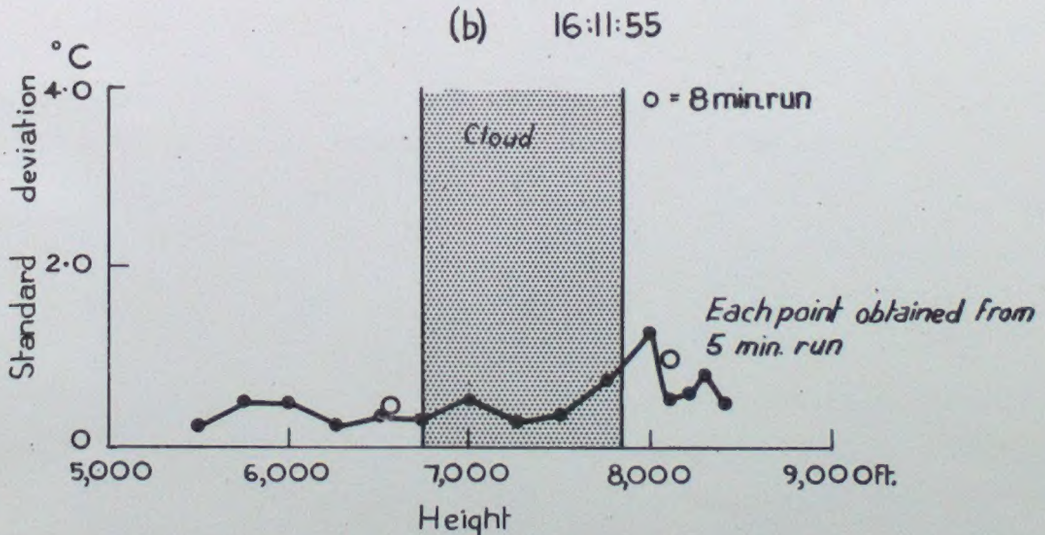
Standard deviations of frost point on level runs



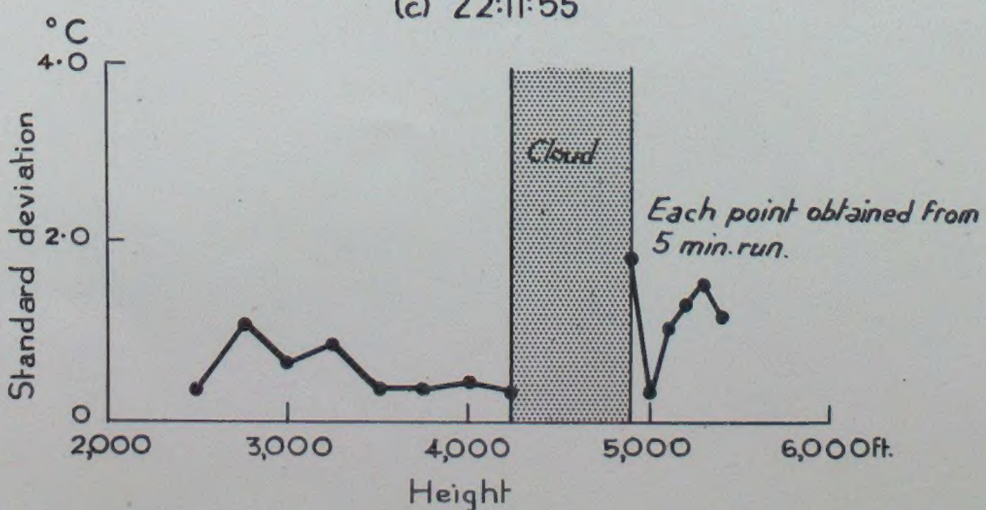
(a) 14:11:55



(b) 16:11:55



(c) 22:11:55



(d) 28:11:55

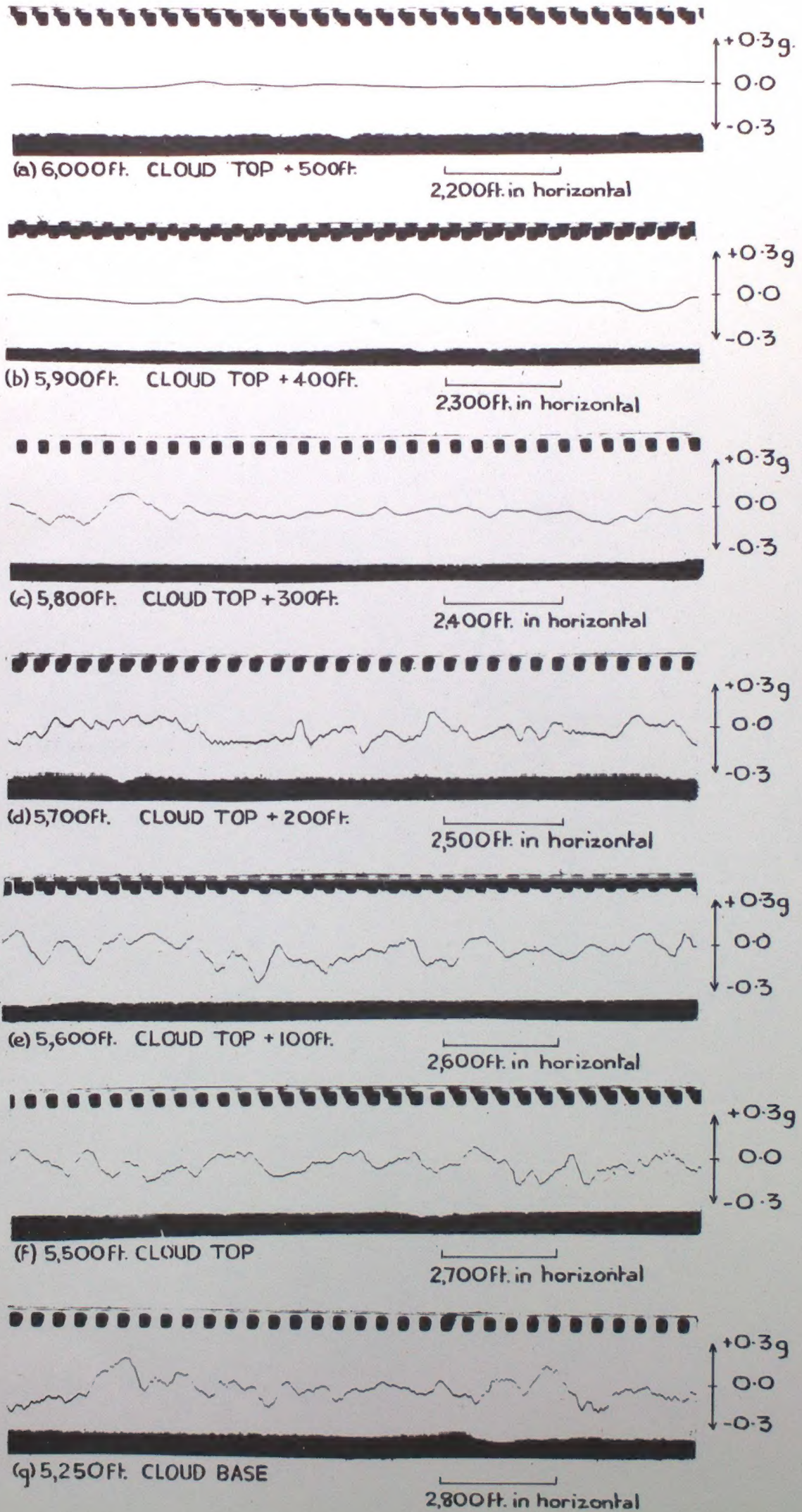



Fig.5 Accelerometer records for 14:11:55